

SLMS™ Athermal Technology™ for UV and Cryogenic Applications

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NASA MSFC Phase II NAS8-02114, Drs. Andrew Keys and Phil Stahl

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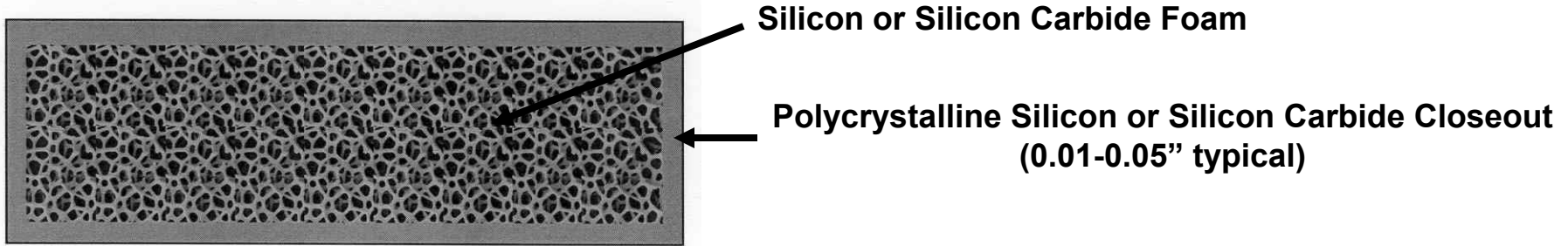
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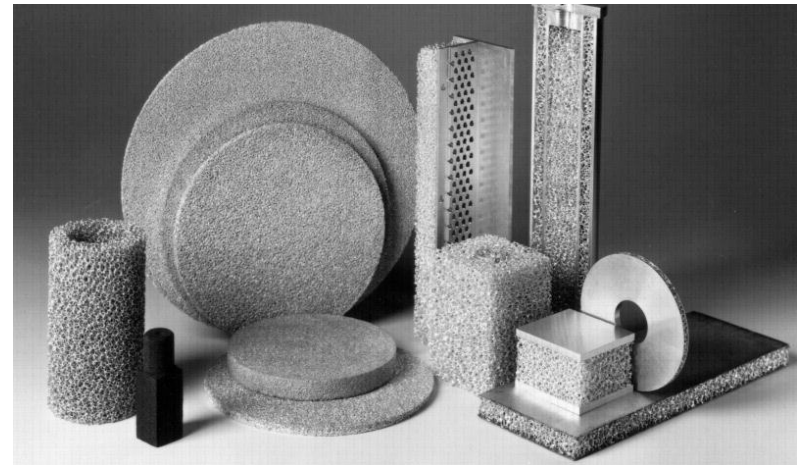
- **What is SLMS™?**
- **Manufacturing Process**
- **Material Properties**
- **Performance Examples**
- **Cryogenic Testing and Qualification at NASA MSFC**
- **Summary**
- **SLMS™ Forecast – What's Next?**

What is SLMST™?

- SLMST™ have a foam core (70-95% porosity) enclosed by a continuous CVD polycrystalline shell (like an M&M)
- Silicon and Beta-Silicon Carbide (SiC-SLMST™) now available



- Foam is Open-Cell (Reticulated)
- Pores are 12-14 sided polyhedra with pentagonal or hexagonal faces
- Pore Diameter: 10-100 per inch
- Foam Density: 5-30% of Solid
- Foam Modulus: $E_{\text{foam}} \sim E_{\text{solid}}(\rho_{\text{foam}}/\rho_{\text{solid}})^2$
- Foam core can be CNC machined to virtually any shape to ± 0.002 inch



- New 60 cm facility on-line September 2003
- Substrate manufacturing through polishing
 - ⇒ 7-12 weeks (flats and spheres)
 - ⇒ 16+ weeks for aspheres
 - ⇒ 20+ weeks for off-axis aspheres
- ISO 9001:2000 Quality Plan Established and Approved by Major System House
 - ⇒ Preparing for Certification in '04



Silicon Foam
4 – 6 weeks



Polycrystalline Silicon Close-out
2 – 4 weeks



Polished CVD Silicon
1 – 2 weeks



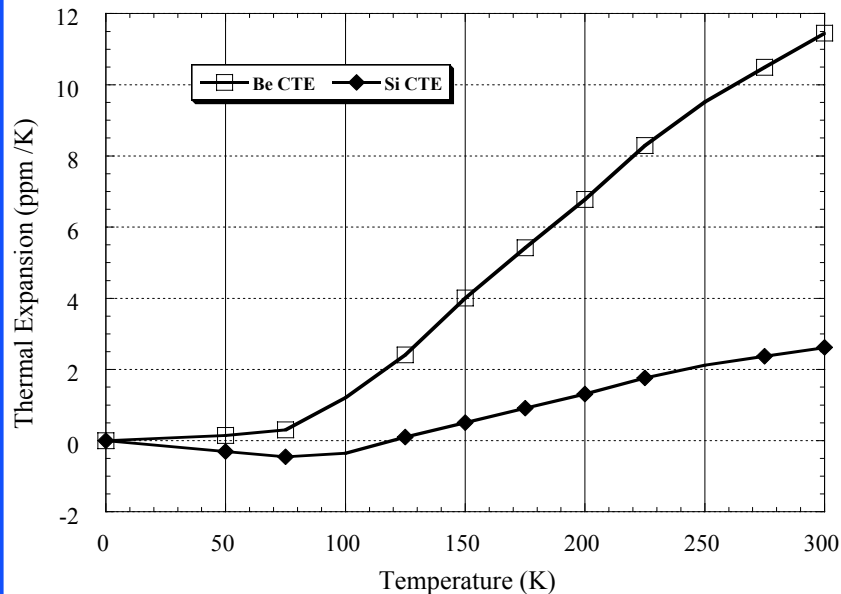
**HEL Coatings for Operation at
HF, DF and 1.315 μ m**



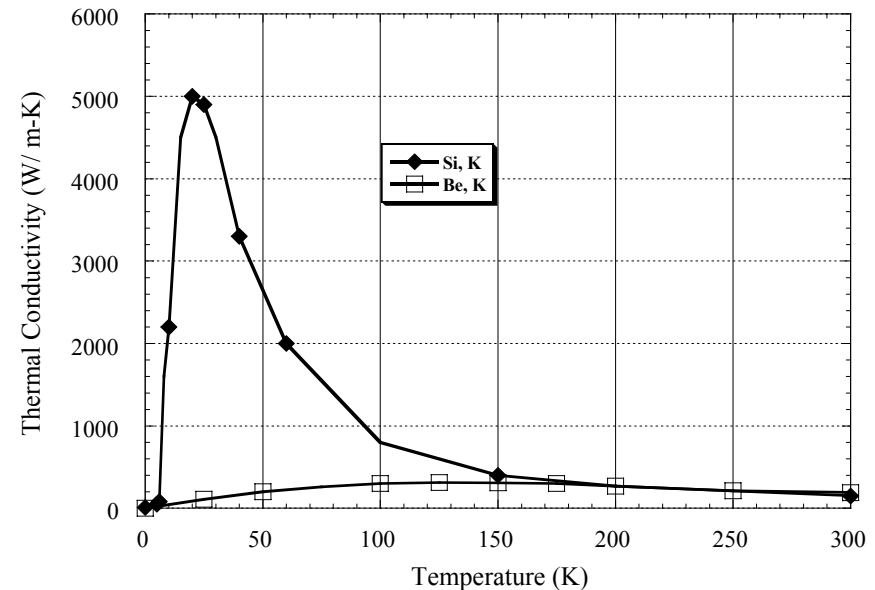
Silicon Superior to Beryllium

- Silicon has superior performance to Beryllium at cryogenic temperatures and is greater than an order of magnitude cheaper to polish to surface figure of <63 nm p-v and surface roughness <10 Angstroms rms.

Linear Coefficient of Thermal Expansion for Silicon and Beryllium



Thermal Conductivity of Silicon and Beryllium



NASA MSFC UV Demonstrator- Phase I

Generation 1 UV Mirror

- Silicon Lightweight Mirrors For Ultraviolet And Extreme Ultraviolet Imaging Mirrors
- NASA needs: 0.5-2.4 m Diameter, IR-EUV Performance (figure/finish accuracy)

Schafer*Los Angeles Operations*

UV Demonstrator Mirror Results

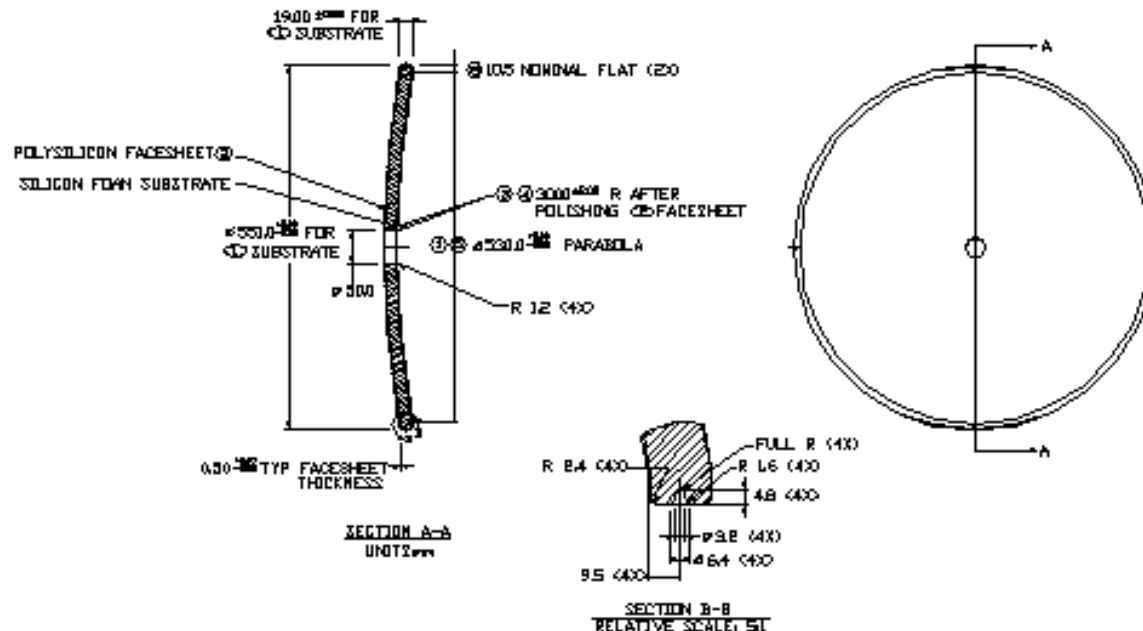


Figure of Merit	Specified Value	Results Achieved
Areal density, kg/m ²	< 20	9.8
Surface figure at 80% CA, waves rms @ 633 nm	0.02	0.021
Surface figure at 95% CA, waves rms @ 633 nm	N/A	0.027
Surface roughness, Å rms	10	4
Surface quality (scratch/dig)	60/40	20/20

Achieved or exceeded all specifications.

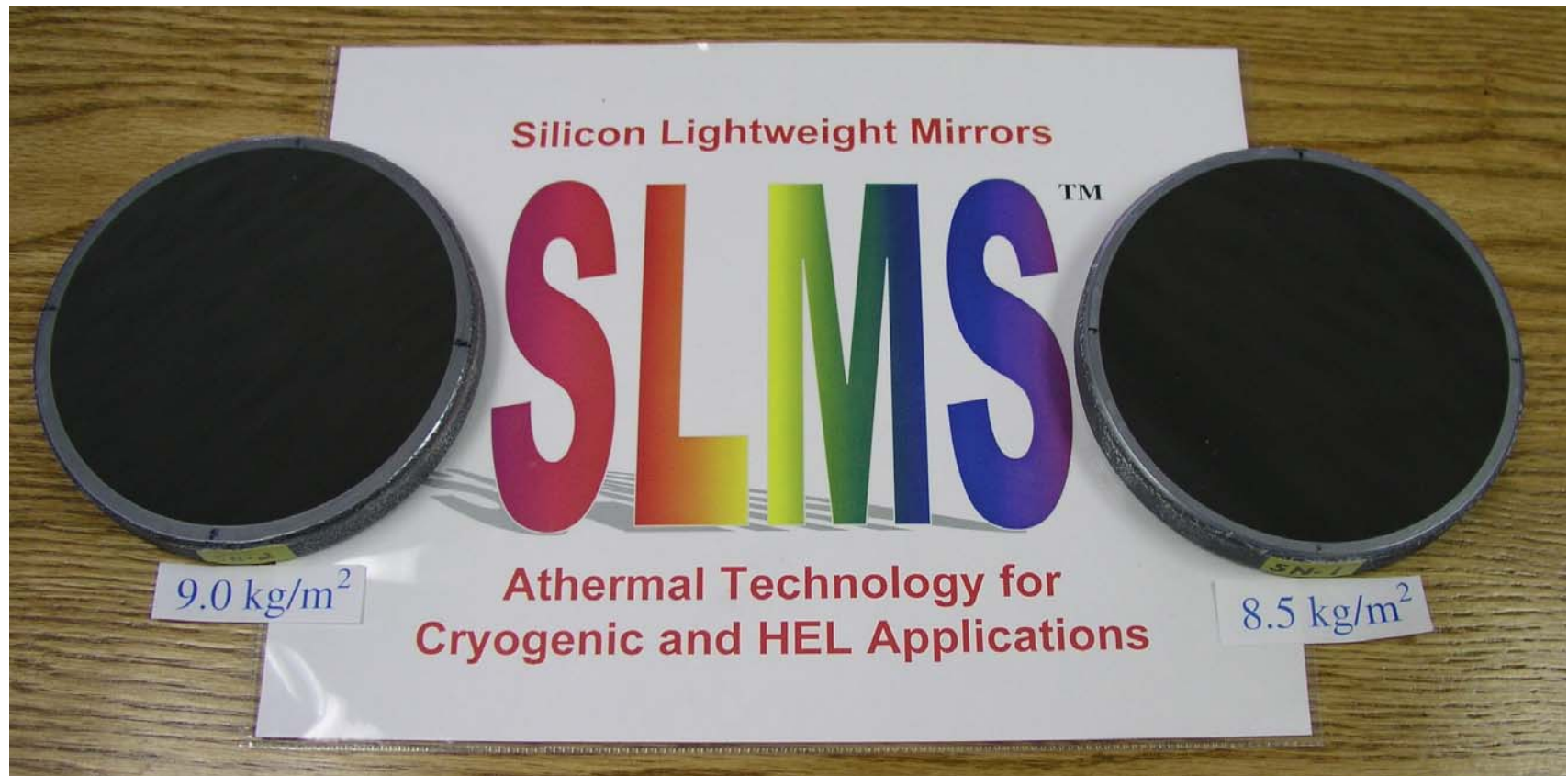
Phase II Project: Solar High Angular Resolution Photometric Imager (SHARPI)

- **Mirror application:** Studying the Sun on the scale of magnetic flux tubes and the photon mean free path in the photosphere has been a high-priority goal of solar physics for well over two decades. The highly structured and intermittent magnetic field in the solar atmosphere is the source of solar activity and its terrestrial effects. SHARPI is a concept for an experiment to achieve 0.1-arcsecond solar imaging using a lightweight, ultra-precise 55-cm telescope in the far ultraviolet (160 nm continuum, eventually emission lines including Lyman alpha and C IV).
- Primary Mirror: 530 mm CA, concave parabola, 3000 mm radius of curvature, 20 mm thick, 50 mm diameter pupil



AFRL/VSSV DOTS Demonstrator Mirrors

- AFRL/VSSV Phase I: DOTS Demonstrator Mirrors – Required Radius of Curvature Control and Matching



**Exceeded all requirements and
almost all goals.**

Latest Delivery Details

- AFRL/VSSV Phase I: DOTS Demonstrator Mirrors

Figure of Merit	Goal	Requirement	Mirror 1	Mirror 2
Areal Density	10 kg/m ²	10 kg/m ²	9 kg/m ² Exceeded goal	8.5 kg/m ² Exceeded goal
Radius of Curvature	600 mm ± 0.3% (±1.8 mm)	600 mm ± 0.5% (±3 mm)	598.6323 mm (600 mm ± 0.23%) Exceeded goal	598.63228 mm (600 mm ± 0.23%) Exceeded goal
Δ ROC between mirrors	<40 μm	<40 μm	0 Exceeded goal	0 Exceeded goal
Surface Finish	≤ 20 Å rms	≤ 30 Å rms	30 Å rms Meets requirement	19 Å rms Exceeded goal
Surface Quality	40/20 scratch/dig	60/40 scratch/dig	40/20 Meets Goal	40/20 Meets Goal
1-G sag/1 st frequency (kinematic mount)	<4.875 nm RMS/ >1785Hz	<4.875 nm RMS/ >1785Hz	1.55 nm RMS/1802 Hz Exceeded goal	1.55 nm RMS/1802 Hz Exceeded goal
1-G sag/1 st frequency (tangent mount)	<4.875 nm RMS/ >1785Hz	<4.875 nm RMS/ >1785Hz	2 nm RMS/5047 Hz Exceeded goal	2 nm RMS/5047 Hz Exceeded goal

- Areal density of 7.4 kg/m² has been achieved for this substrate design
- Specifications are suitable for Infrared to Submillimeter Wave Applications

**Cryogenic Qualification
of SLMS™ at NASA MSFC
with University of Alabama, Huntsville**

NASA UV Demonstrator Mirror

MSFC Small Optic Cryogenic Test Facility



4' Cryogenic Chamber Capabilities

Vacuum Chamber: 4' diameter x 8' horizontal cylinder with helium gas cooled test volume

Test Volume Dimensions: 39.8" ID x 87.8" long

Ambient temperature vacuum level: $< 5 \times 10^{-6}$ Torr by turbomolecular pump

Temperature Range: 300K to 12K

Refrigeration and Capacity: Closed-loop gaseous helium expansion cycle capable of 1 kW at 20K

Optical View Ports: A 5.875" BK7 window is existing. Additional optical port(s) are in development.

Seismic Environment: Characterization test is planned

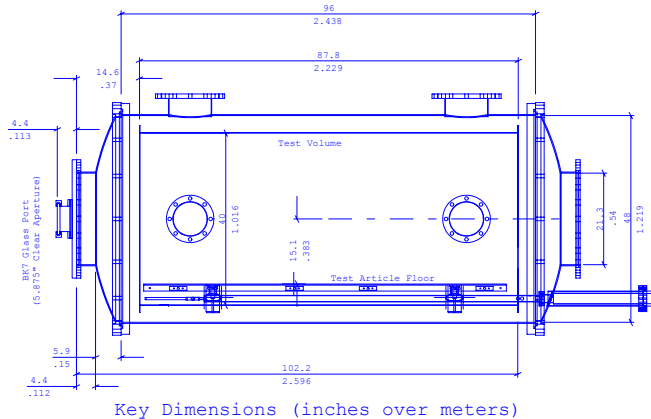
Optical Instrumentation: WaveScope, PhaseCam, and IPI (details are available)

Thermal Instrumentation: Silicon diodes and thermocouples
Additional electrical/fluid feedthroughs are available

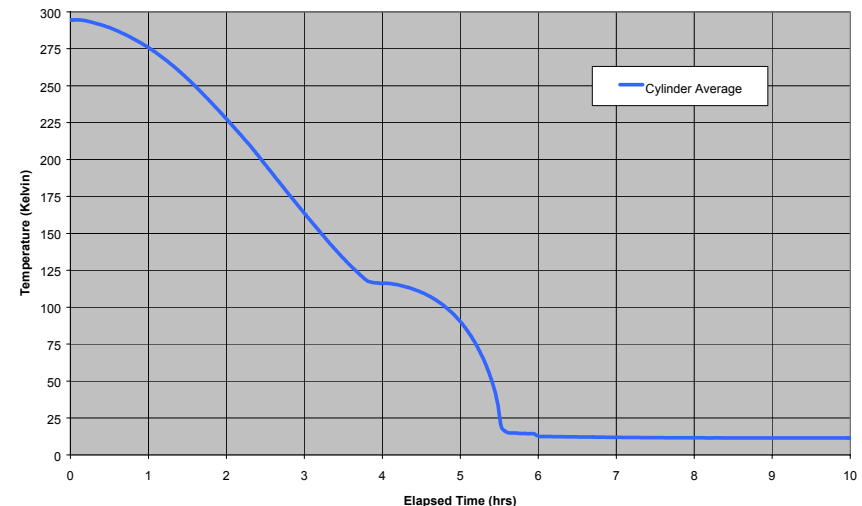
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XRCF 4' Cryogenic Chamber

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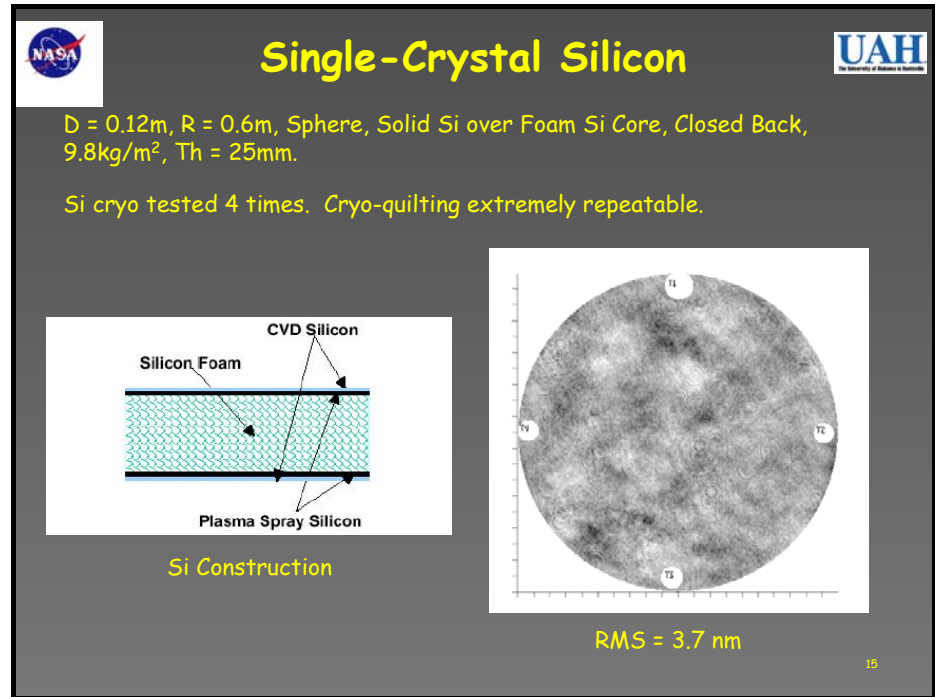
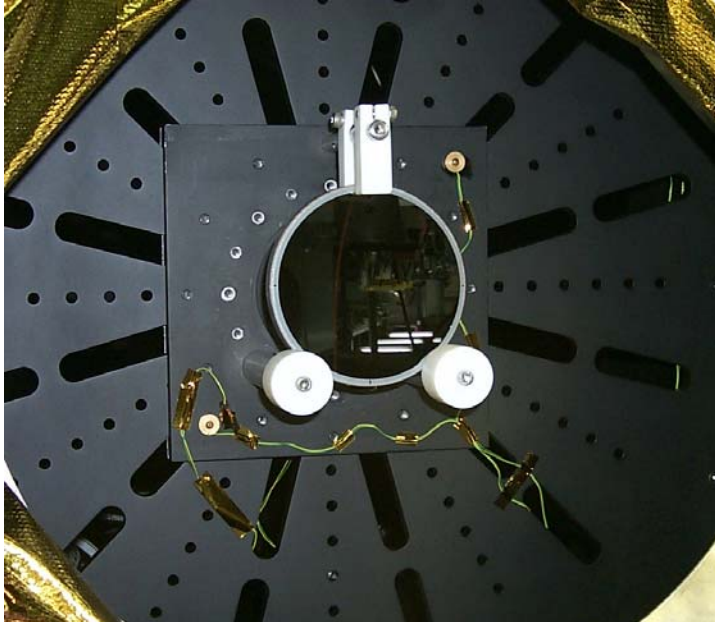
CryoOptical Test Chamber
Shroud Verification Test



Free Mounted, Uncoated SLMS™

- Uncoated 5" dia. Spherical SLMS™ with 600 mm Radius of Curvature freely mounted in the cryo chamber (NASA UV Demonstrator Mirror)
 - As-delivered Figure accuracy was $\lambda/37$ rms HeNe over 95% CA
- Measured nominal surface degradation difference (300 K-76 K, 300 K-27 K)
 - Measured value of $< \lambda/60$ rms HeNe over 95% CA
 - Measurement includes contribution of cryo-chamber window deformation
 - Difference in surface degradation from 90% to 99% CA was ~ 1 nm rms

Actual surface degradation difference 3.7 nm rms



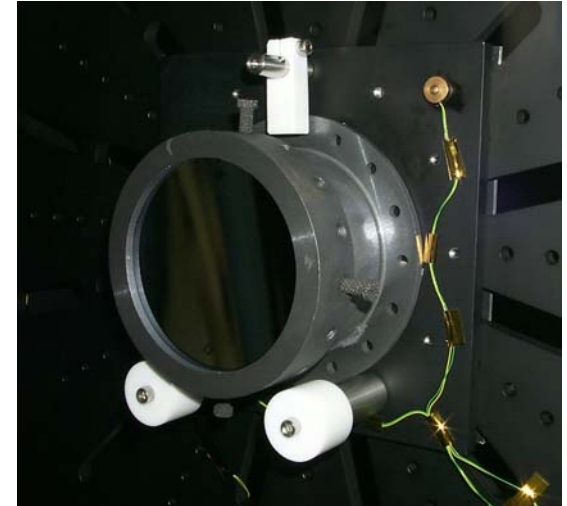
Uncoated SLMS™ Bonded to Cesium Mount

- MSFC Proprietary “Fish Cooker” Used for Joining Process

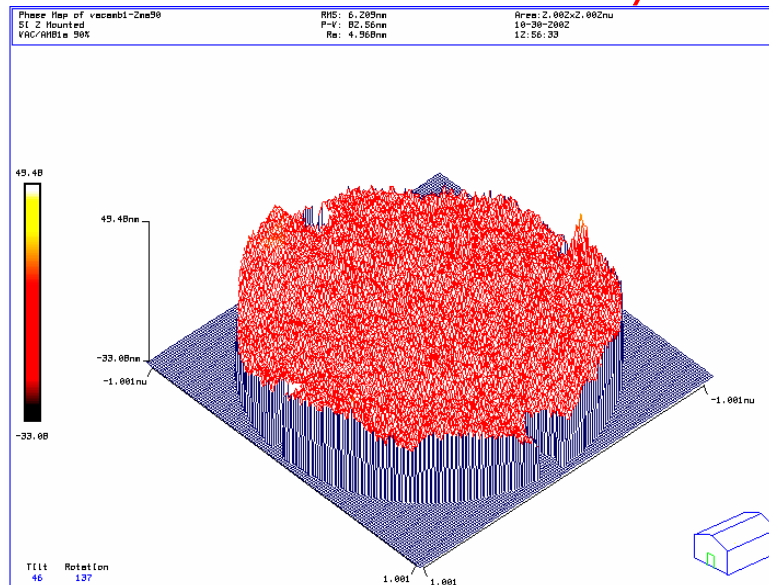


Cesic Mounted Uncoated SLMS™

- SLMS™ bonded to the Cesic® mount
- SLMS™-Cesic® assembly freely mounted
- Ambient figure showed a slight bit of astigmatism -
 - Inherent in PROTOTYPE Mount
- 300 K Surface figure was $\lambda/17$ rms HeNe at 90% CA
- Surface degradation difference (rms HeNe at 90% CA)
 - 300-27 K: $\lambda/13.6$
 - 300-77 K: $\lambda/14.7$
 - 300-193 K: $\lambda/22.6$

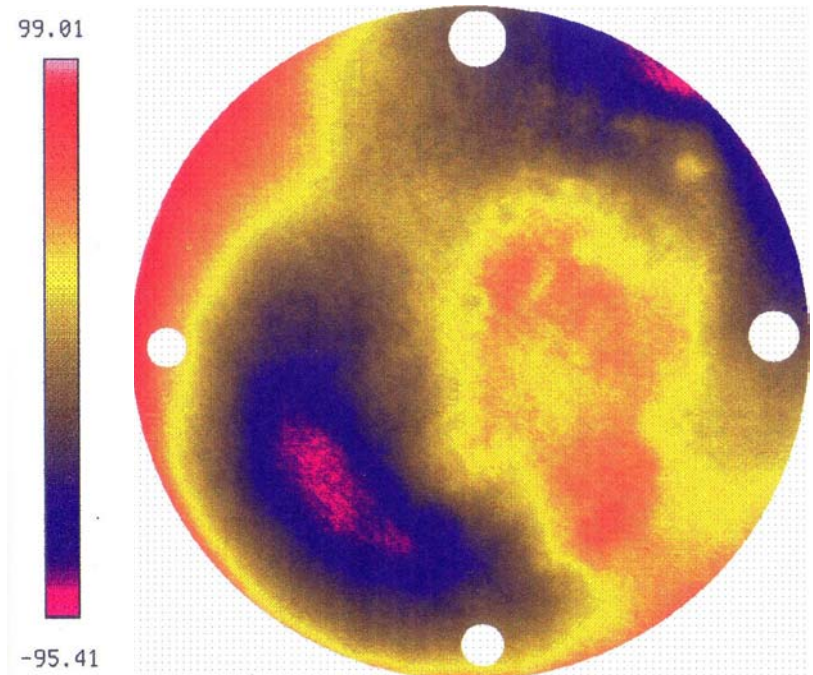
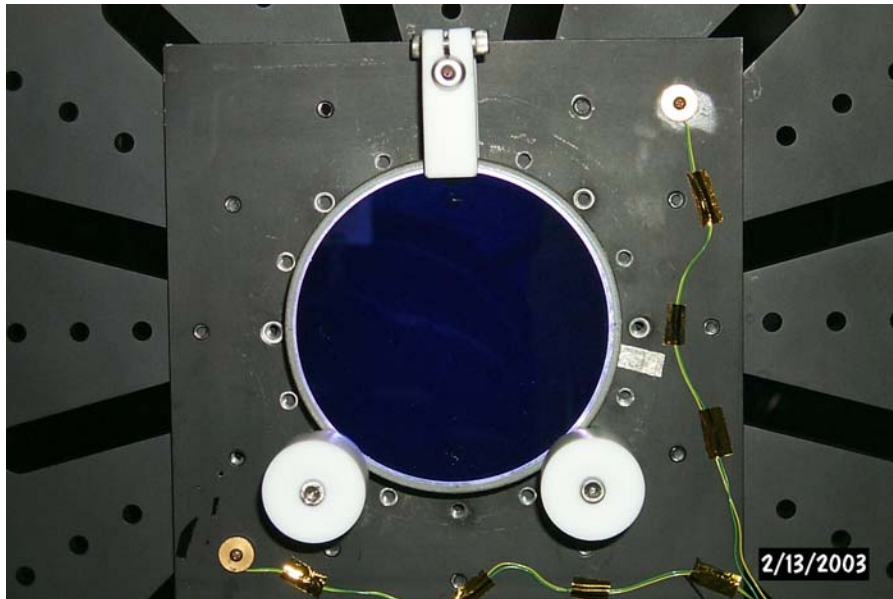


- After one cryo cycle the difference in surface deformation was $< \lambda/100$ rms HeNe at 90% CA.
- There was NO HYSTERESIS.



Free Mounted Coated SLMS™

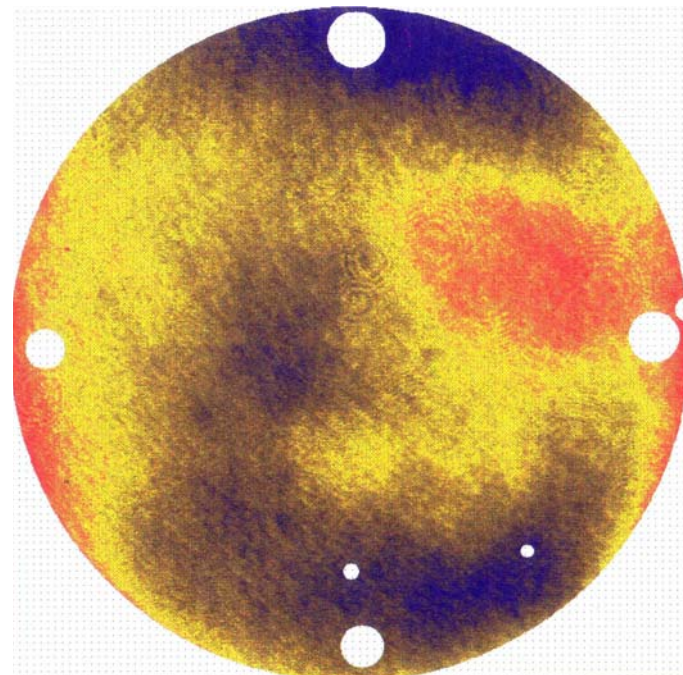
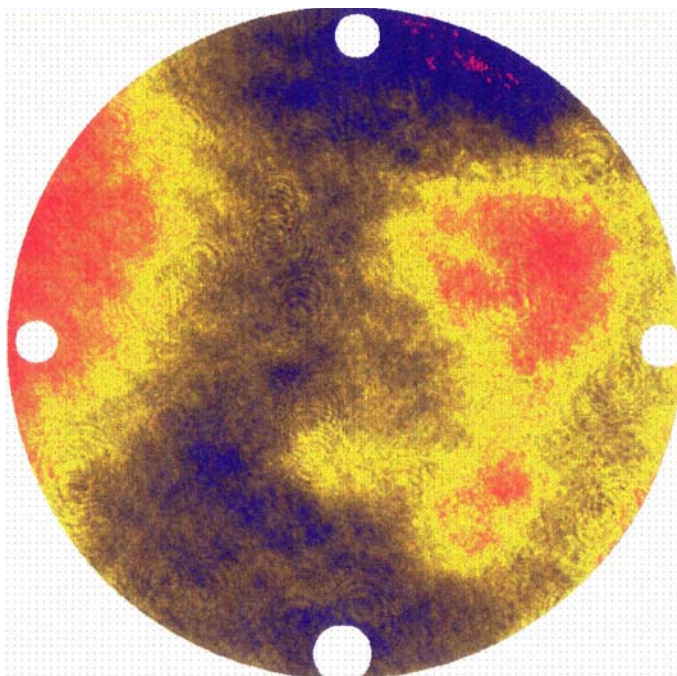
- After testing at MSFC, the 5" dia. SLMS™ was sent to AFRL for deposition of a very low absorption (VLA) ABL ($1.2\mu\text{m}$ - $1.4\mu\text{m}$) coating.
- 20-layer pair oxide-based coating with a thickness of $5\mu\text{m}$.
- The coating process reduced the ambient figure slightly from $\lambda/20$ to $\lambda/17$ rms HeNe at 90% CA, a difference of $> \lambda/100$ rms HeNe.
- Coated SLMS™ mirror freely mounted in the cryo chamber



Uncoated/Coated Differential Comparison at Vacuum/27 Kelvin

Uncoated: 10.40 nm rms

Coated: 10.92 nm rms



Difference of 0.5 nm rms!!!

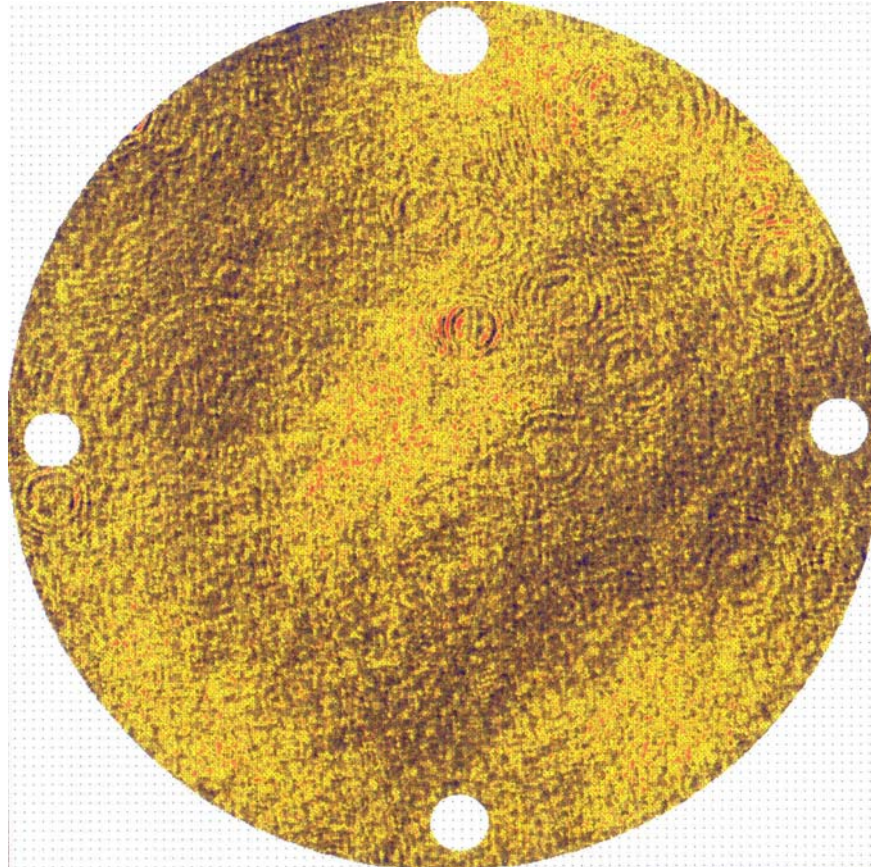
Coated Differential Comparison at 27 Kelvin/80 Kelvin

Differential Surface Figure = 2.0 nm rms

11.41



-11.79



Summary

- Excellent areal density, surface figure, roughness and quality achieved
- 5" dia. spherical uncoated and VLA coated SLMS™ cryogenically tested at MSFC to 27K
 - ⇒ Thermal behavior of uncoated and coated VLA SLMS™ the same
 - ⇒ Surface figure difference from ambient to cryo is $>\lambda/100$ rms HeNe
 - ⇒ Surface figure difference due to VLA coating is $>\lambda/100$ rms HeNe
- SLMS™ bonded to a precision Cescic® optical mount cryogenically tested at MSFC to 27K
 - ⇒ Athermal behavior of a SLMS™-Cescic® lightweight optical system demonstrated

SLMS™ has outperformed mirrors made by major systems houses and optical vendors as reported by NASA MSFC and UAH at 2003 SPIE.

SLMS™ Achieves or Exceeds the Performance Requirements for Vacuum-Cryogenic Infrared Mirrors such as those required for Scientific Imaging, Military Imaging, and Transformational Communications Missions while providing Lower Areal Density.

- Deposition of high energy (50-100 kW/cm²) at 1.315μm with subsequent cryogenic tests have been discussed with AFRL and Major Systems Houses – STILL LOOKING FOR A HIGH POWER LASER!!!
- Generation 2 – Extreme UV Demonstrator Mirror (UVDM2)
 - ⇒ <5 kg/m², <0.005 waves rms HeNe figure accuracy, <2 Angstroms rms finish
- Active Cooling <5 K
- Diameter >50 cm